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Highly Accurate Inflatable Reflectors

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FOREWORD

This report was submitted by L'Garde, Inc., Newport Beach, CA 92663, with the Air Force Rocket Propulsion Laboratory, Edwards AFB, CA 93523, under Air Force Project Task 286400JY. The report gives a description of the work done to investigate the feasibility of attaining .1mm RMS accuracy on an inflatable reflector for use in space.

This report has been reviewed and approved for publication in accordance with the distribution statement on the cover and on the DD form 1473.

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For Phase I of this SBIR program, analytic and experimental studies were performed to see if inflatable reflectors could be made with rms surface errors of less than 0.1 mm (a 1.0 mm capability had already been demonstrated). Surveys of film vendors resulted in the selection of several approaches including heat forming, laser-welding of gores, prestretching of gores, and gore reinforcement. Results show that inaccuracies less than 0.1 mm rms are feasible. The preferred approaches require heat forming, use of thick films and improved accuracy of flat pattern calculation.

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Preface

This study was performed for the USAF Rocket Propulsion Laboratory as part of the Small Business Innovation Research program. The Project Manager was Lt. James A. Chapman, AFRPL/DYS (805)277-5164.

The Program Manager at L'Garde was Gordon Veal. He was assisted by James Trailer (laboratory support) and Mitchell Thomas (Analysis).

Helpful discussions were had with representatives of many plastic film manufacturers and processors (see Appendix A).

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ILLUSTRATIONS

1. INTRODUCTION

In the 1960's, NASA put considerable effort into inflatable space structures, including Echo I and II, PAGEOS, and Explorer IX and XIX. Overall, inflatables in space have been successful, and significant advantages to their use demonstrated. Inflatable space systems invariably require less packaged volume, are lower in weight, and cheaper through both development and production phases than competing mechanically-erected systems. If inflatables can be made to work as large reflectors in space, they will provide cost effective solutions for a variety of needs. In fact, because of greatly reduced launch costs, the use of inflatable reflectors for antennas or solar collectors can make possible important missions that otherwise would be cancelled or postponed; launch cost savings alone can run into tens of millions of dollars for a single mission. The study reported here was to determine the feasibility of using large space inflatable reflectors for mm-wave antennas or solar collectors.

In the 1970's, NASA's effort decreased, but many inflatable devices for use in space were built for the USAF. The USAF studies were for inflatable decoys or targets which typically had a short lifetime. In many cases severe environmental restraints on these systems (such as nuclear blast exposure) required development of new materials and construction techniques for these devices. Again inflatable devices were traded against mechanical systems to do the same job and invariably won the competition due to lower weight and volume.

For fear of meteoroid puncture, and loss of inflatant, the NASA inflatable-systems effort turned early to self-rigidizing systems, so that inflation was used mainly as a forming erection mechanism. Many of the advantages to space inflatables, such as ruggedness, damped dynamics, and low weight were lost by this. Recently, we have shown that the meteoroid problem was grossly overestimated (reference 1) and that inflatable systems can remain operating for ten years or more by replacing the lost gas while maintaining a low total system weight.

Figure 1 shows a typical feasible space inflatable reflector. Here a paraboloid is joined to a conical structure (which might hold microwave receiver) at a rigid toroidal interface. The paraboloid and cone shapes are maintained by internal pressure. Such is the power of this technique that a 700-meter diameter reflector could be carried on a single shuttle payload -- limited by the maximum shuttle payload weight (30,000 kg). This package would use up less than one-third of the volume in the shuttle bay.

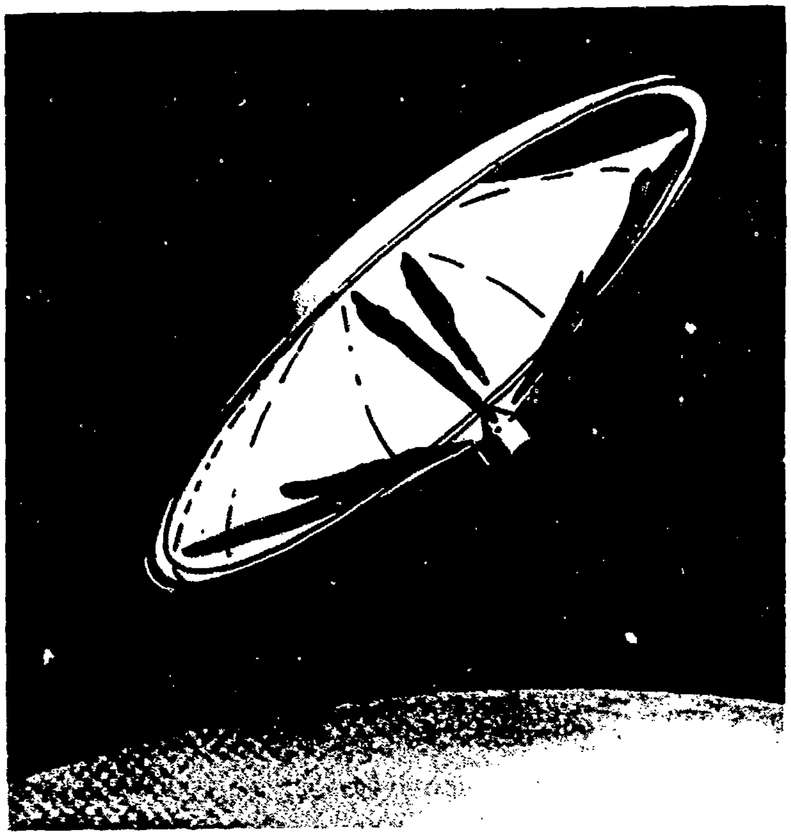

Figure 1. Fully-inflated space antenna concept.

NASA Contract NAS1-16663 culminated in the construction of 3-meter diameter parabolic membranes, inflating them, and measuring the surface accuracy (reference 2). These were constructed of flat elements (gores) connected with tape at the seams (Figure 2). The facility developed, which was also used in the present study, was constructed around a 3-meter optical bench and laser used to map the surface of the paraboloid. Figure 3 shows a result of a measurement of paraboloid accuracy across a typical chord of the paraboloid, and it is seen that the paraboloid maintains its accuracy to better than 1 mm rms. This type of accuracy is usually good enough for most applications where the microwaves' wavelength is greater than 2 cm (frequencies less than 15 GHz). However, to extend the use of such systems to the millimeter wave regime, an advance in the state of the art is needed.

USAF current needs that would require the higher accuracy include mm-wave surveillance radiometers, space radar, and solar concentrators (solar rocket). The goal of the current study is to reduce the 1 mm rms surface error that has been demonstrated down to 0.1 mm rms surface error as required for mm-wave devices.

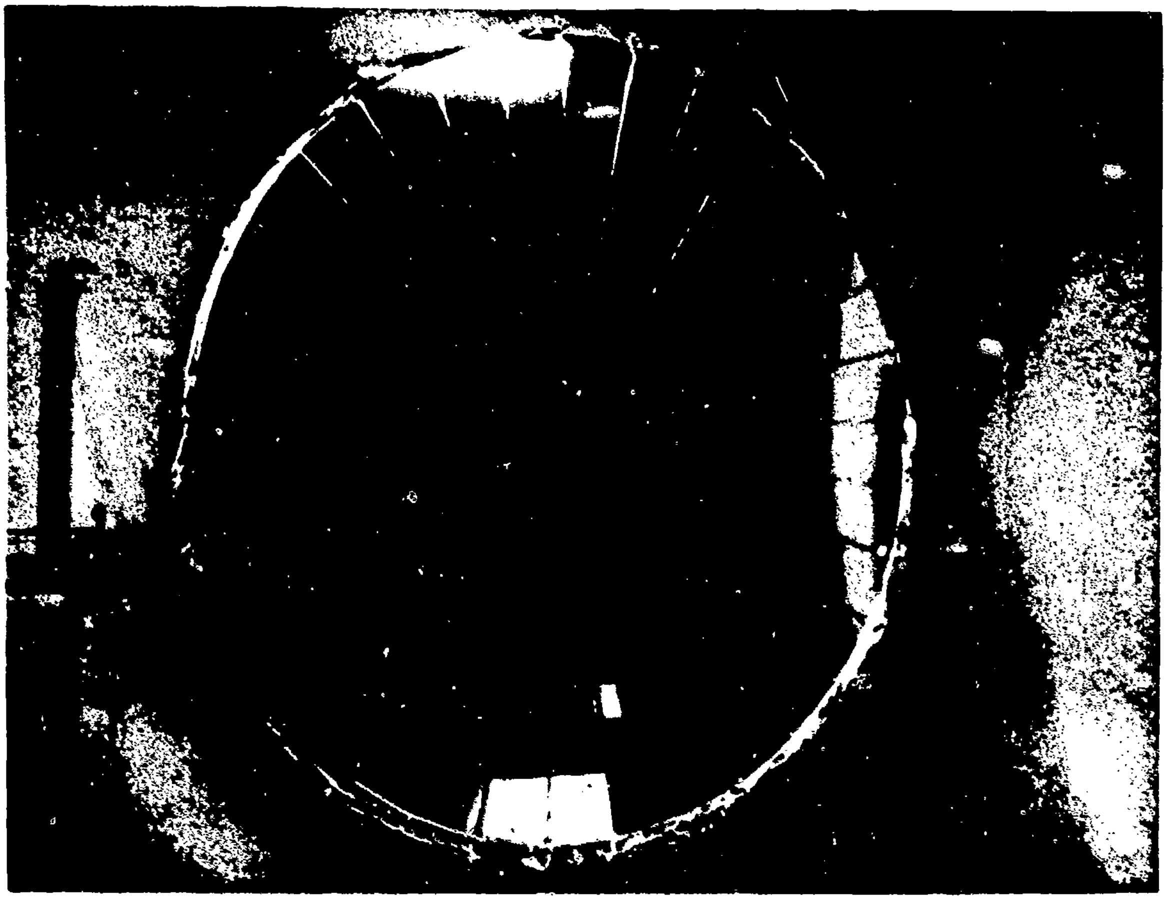

Figure 2. Three-meter polyester paraboloid (32 gore).

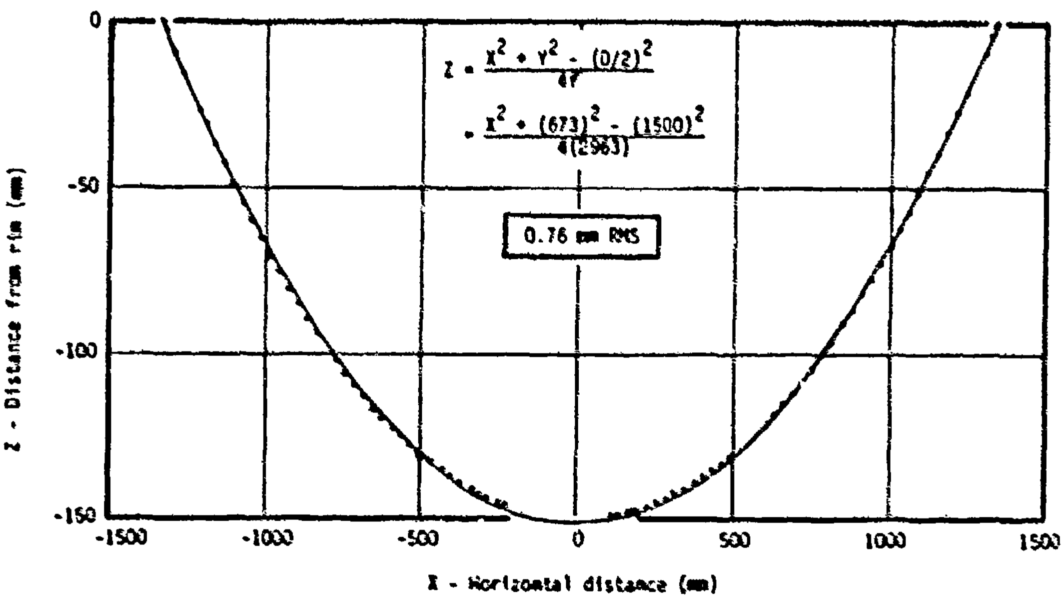

Figure 3. Cross section of polyester paraboloid (13 MPa film stress).

Figure 4 shows the measured surface slopes corresponding to the data in

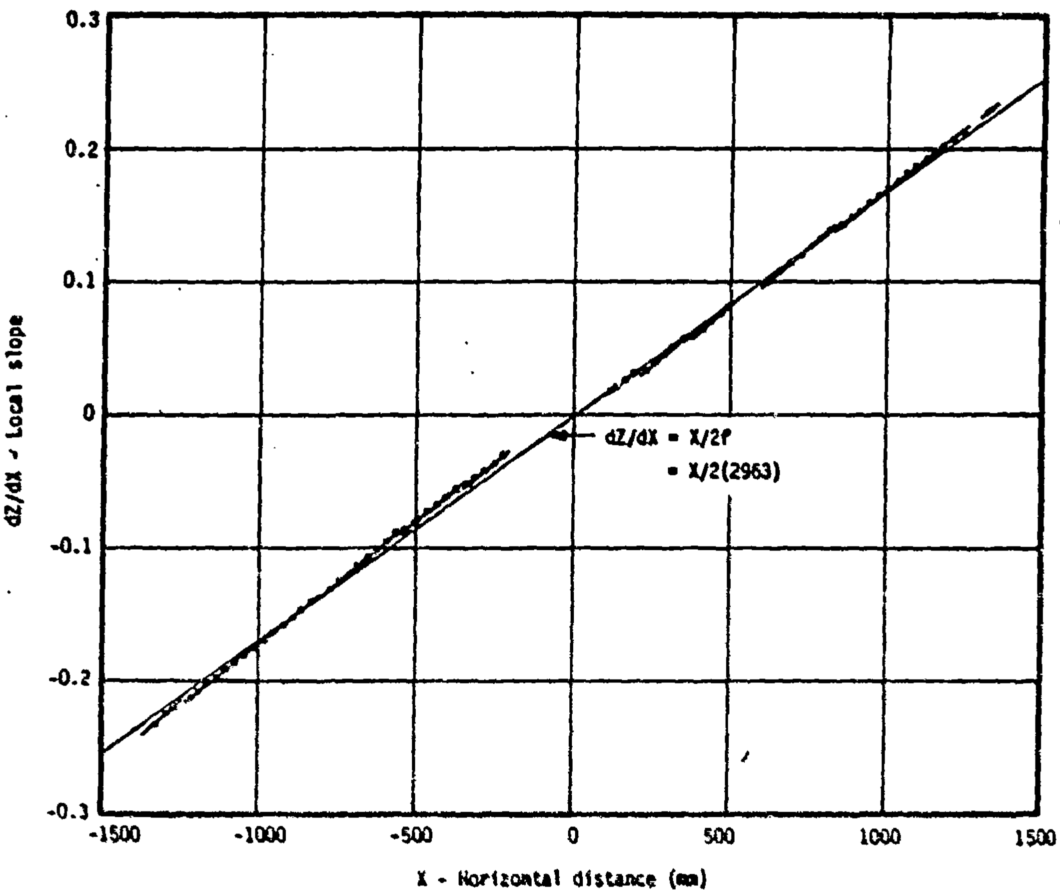

Figure 4. Slopes of polyester paraboloid (13 MPa film stress).

Figure 3. Some error is being caused by the tape used to join the gores -- since the discontinuities occur at taped interfaces. The main thrust of the current study was to examine new seam configurations to see if this error could be reduced. A plot of the deviations of the inflated surface from a true paraboloid is shown in Figure 5 from reference 2. When plotted in this manner, the deviations appear to be regular as opposed to random which suggests they are caused by a systematic error and might be correctable. The remainder of this report details the efforts performed on this study to find and correct the source of error. As will be shown, the results are encouraging.

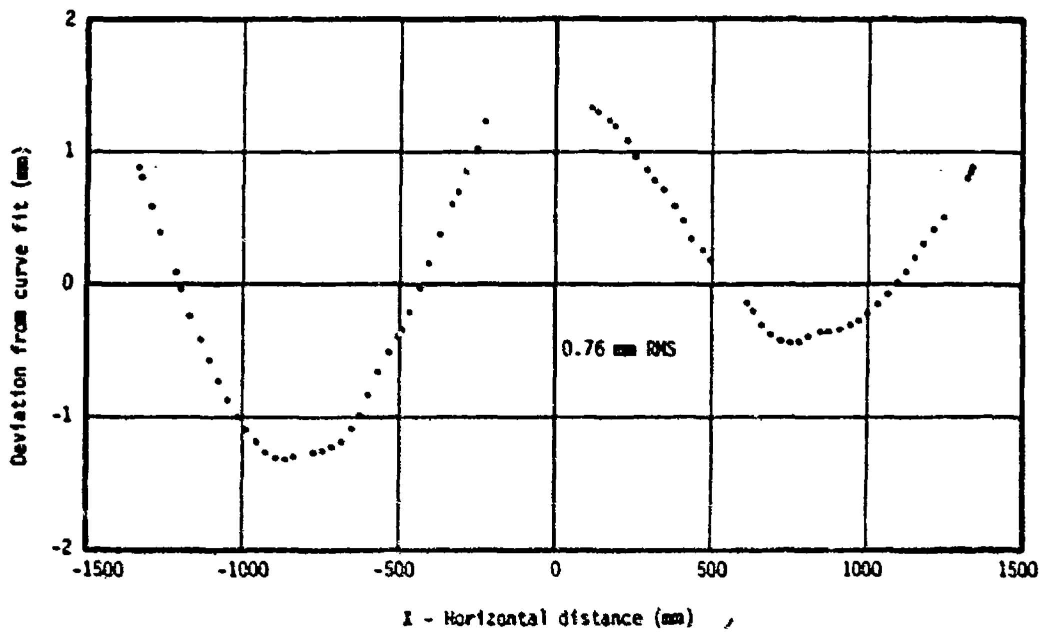

Figure 5. Inaccuracy of polyester paraboloid (13 MPa film stress).

2. SURVEY

Before proceeding into the experimental investigation of precision forming of inflatable reflectors, the plastics industry was surveyed to determine what had already been done. The companies contacted are listed in Appendix A. The important factors learned about films as applied to our problem is summarized below.

Several people were contacted at DuPont, with the main information coming from Bob Schlipp. Their Mylar-brand polyester film is normally extruded onto a chilled roller. To give it its strength it is stretched in both directions (3000%) and annealed at 200°C. Physical properties of their films are measured in both stretched directions and are available. They have experimented with uniaxially stretched film. For our application the T* and TR* types of Mylar may be applicable.

Ed Healey of Allied Corporation pointed out that they sell the amorphous (unstretched) polyester in as thin as 1 mil thickness. Petra is their trade name for the thermal formable film. They recommend forming it at 350°C. Care must be taken to avoid too hot or too long exposure or the film will crystallize and become brittle. This film could be used to vacuum form at elevated temperature.

ICI Americas, Inc. manufactures a polyester (Melanex) in thin sheets. They mentioned that we would have difficulty stretching it ourselves and doing it evenly. They thought we should contact William E. Young & Co. relative to ultrasonic sealing. William E. Young was contacted and it was discovered that the ultrasonic sealing process gave a very weak bond. The material could be pulled apart without damage to each layer. Young suggested IR welding using a laser and volunteered to try it for us if we sent the material to him.

Normal heat sealing was discussed with Plastic Manufacturers, Inc. (Bill Seiler). They supplied the polyester panels for ECHO balloon satellites. They do not recommend heat sealing of polyester because the precise temperatures needed are critical to success. In general, heat sealing is done by laminating with polyethylene first.

Although tape could be made from material stretched in one direction only, to give low strength along its length and high strength sideways, it was not readily available for use on this study.

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*DuPont designations for high tear-strength film.

As a result of these discussion and preliminary testing, it was decided to test reflectors made by the following processes:

1. Thin film and taped seams, as done on the earlier NASA contract.
2. Thin film and taped seams, but with the film stretched to its final length before taped.
3. Thin film and taped seams, with tape added in hoop direction to add stiffness to compensate for the added stiffness of the tape along the seams.
4. Thin amorphous film, with seams from IR welding.
5. Thin film and taped seams, heat-formed over a spherical mandrel.

In the case of the initially-flat membranes, tests were made on a full unseamed membrane for reference. No such reference was possible for the paraboloids tested.

3. ANALYSES

The analysis performed on this study was to support the testing. A computer code was written to reduce the measured data to determine inflated-membrane shape. The theory used to determine the appropriate flat pattern for membrane gores was revised to include material anisotropicities. The use of an initially-flat membrane to evaluate seams and construction rather than paraboloids was also studied. The discussion below centers on the latter two items.

3.1 Paraboloid Pattern

The FLATE computer code was developed previously by L'Garde to determine the flat-pattern shapes that will result in a paraboloid when inflated. The model is not documented in the literature but it is similar to that of Lyman and Houmard (reference 3). Lyman's model was simplified and did not correlate well with experimental data. His analysis assumed that the inflated shape and the original shape are close, whereas the FLATE model does not. Both models assume uniform physical properties.

For use in construction of paraboloids to reflect cm-wave or longer radiation, the above models are adequate. However, the systematic deviations shown in Figure 5 imply that a more rigorous model will be needed to define the construction of mm-wave reflectors. Changes were made in the model as shown below.

The FLATE code solves for the shape of a body of revolution that when inflated will be a perfect paraboloid. Elements of length in the hoop direction are designated as dc' (before inflation) which becomes the new elemental length dc after inflation. Similarly in the meridional direction, an element ds' becomes a new length ds after inflation. The equations solved are

$$dc = dc' \left(1 + \frac{S_H - \nu S_M}{E}\right) \qquad (1)$$

$$ds = ds' \left(1 + \frac{S_M - \nu S_H}{E}\right) \qquad (2)$$

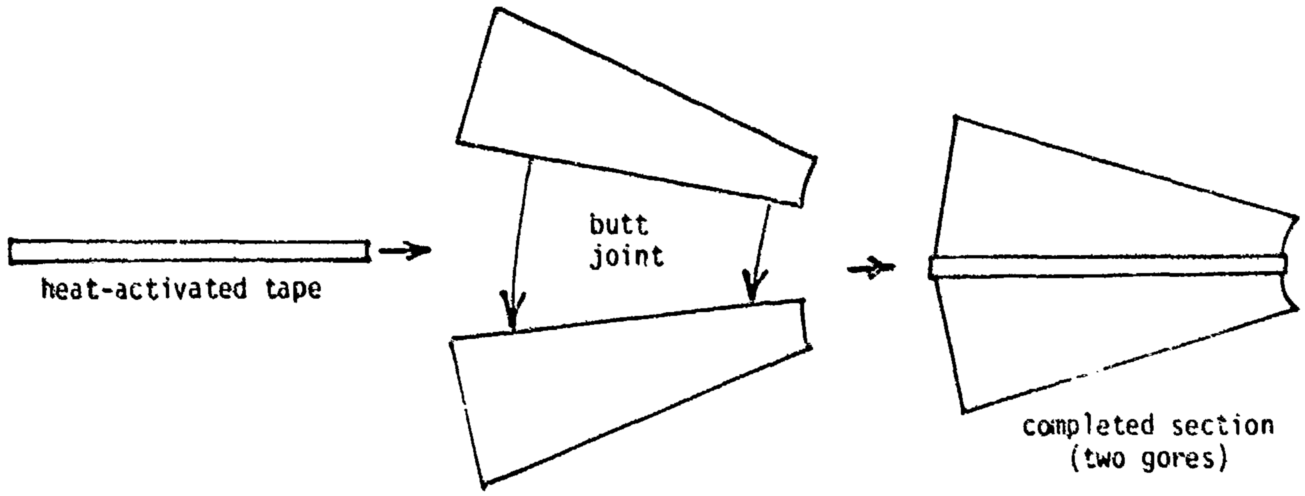
the stresses in the two hoop and meridional directions, S_H and S_M respectively, are given by (reference 4)

$$S_M = PR_H/2t \tag{3}$$

$$S_H = (PR_H/2t)\ (2 - R_H/R_M) \tag{4}$$

where R_H is the radius of curvature of the surface in the hoop direction and R_M is the radius of curvature in the meridional direction. Also P is the inflatant pressure, t is the material thickness, ν is Poisson's ratio, and E is the material modulus of elasticity.

The solution of these equations by FLATE assuming uniform material properties was considered inadequate and revised as follows. The major effect considered was the reinforcing of the material by tape used along the seams. As seen in the sketch below, a gore used in the construction of paraboloid will consist of thin film and tape, with the tape becoming a larger fraction of the gore material as the smaller end of the gore is approached (corresponding to the center of the paraboloid). The construction we examined for the paraboloid had the small-ends of the gores joined to a circular disk which was the very center of the paraboloid (see Figure 2). Thus the stiffness of the membrane material becomes effectively greater as the center of the paraboloid is approached, due to the increased amount of seam tape versus the gore film.



Layup of Inflatable Reflector Membrane
(only two gores shown)

The FLATE code was modified to handle this by allowing the film thickness, t, in equations 3 and 4 to vary with length along the gore. The value of t used was a weighted average of thickness considering the tape width, the local gore width, and the thicknesses of the tape and gore materials used. This model should overcompensate for the tape thickness since it is equivalent to assuming that the plastic film and tape merge to become a single material, rather than being joined with adhesive. A more detailed analysis should be performed to determine how much of the tape's physical properties can be coupled to those of the membrane through the adhesive interface, but that is beyond the scope of the present study.

The edges of the gores are very nearly straight lines; Figure 6 shows the

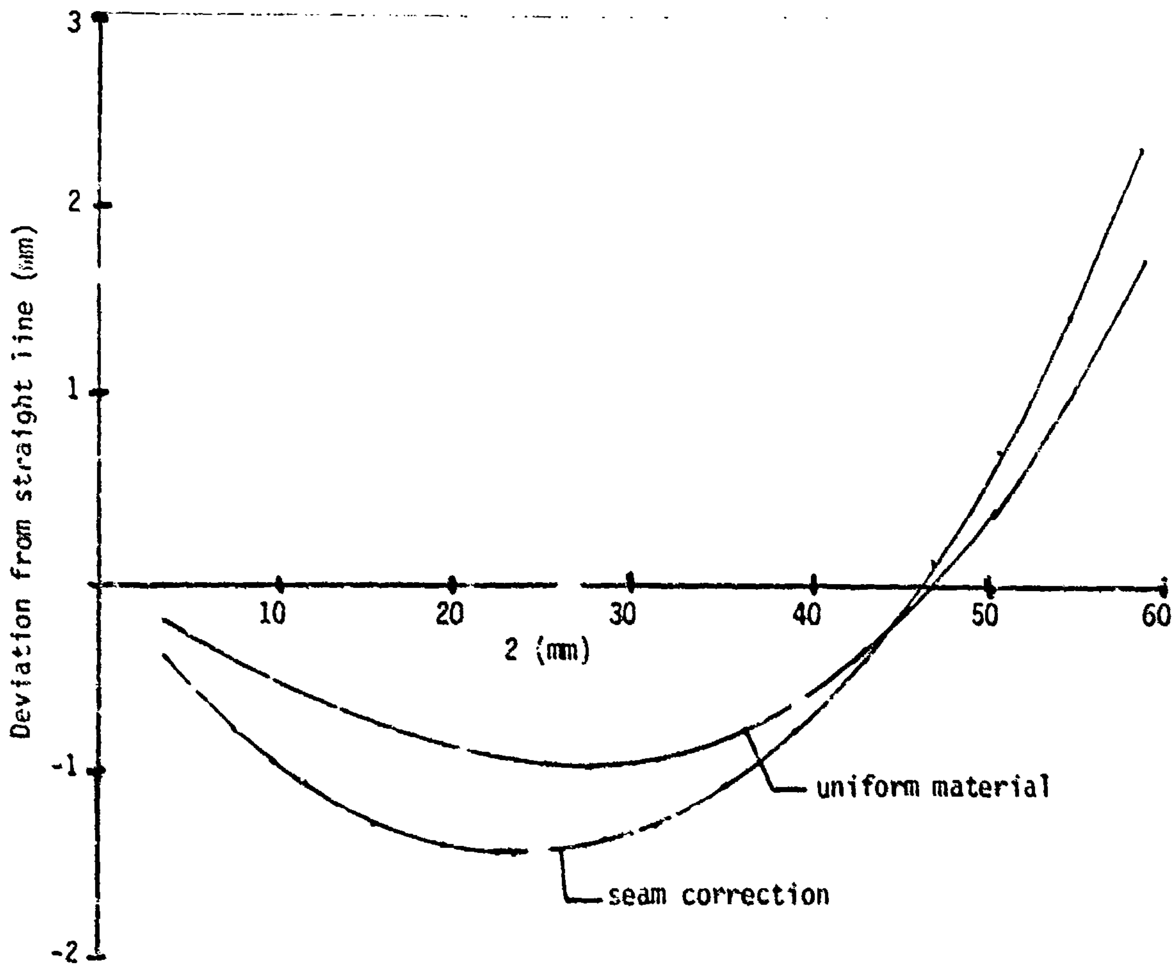


Figure 6. Flat-pattern shape for gore of paraboloid.

deviation from best-fit straight lines for the 24-gore paraboloids built in this study, both using the uniform property model and also the improved model discussed above. In general it can be seen that the gore's edges deviate several mm from a straight line over a running length of 60 mm. As will be shown from the test data in Section 4.1 this variation in gore shape strongly impacts the accuracy of the completed membrane.

3.2 Flat Membranes

Because of ease of construction, simple flat membranes were investigated to determine the effect of seams and construction. The idea was to pressurize initially flat membranes and determine the relative performance of completely uniform membranes and equivalent seamed membranes. The shape of a pressurized membrane constrained at a circumference is given by (reference 4)

$$d = d_{max} \left[1 - 0.9\left(\frac{r}{a}\right)^2 - 0.1\left(\frac{r}{a}\right)^4\right] \qquad (5)$$

where a is the original membrane radius, r is the radial distrance from the center of the membrane, and d is the deflection perpendicular to the original membrane surface. For the flat membranes, the best fit to experimental data of the form of equation 5 was obtained. The curve-fit coefficient was the value of d_{max}.

4. TESTS

Most of the effort during this study was spent on testing the candidate configurations to determine if accuracies on the order of 0.1 mm rms were feasible. The inflated surfaces were mapped using the laser and optical benches as was done on the earlier NASA contract. The experimental setup is shown in Figure 7 and 8. An automated data reduction procedure was developed. The slope

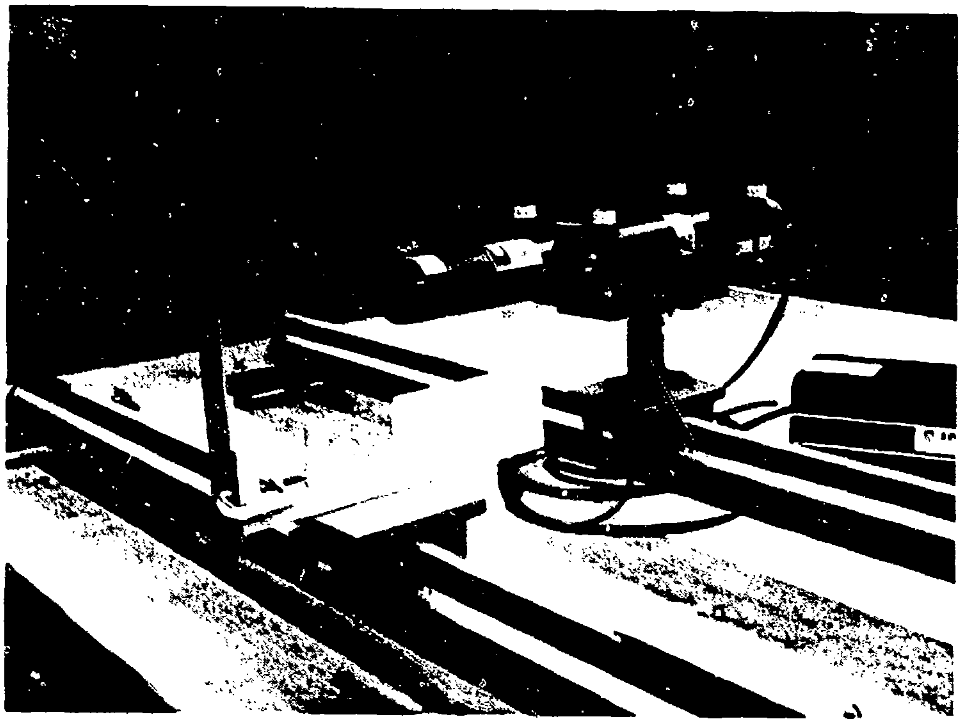


Figure 8. Surface-mapping optical setup

α of the surface was determined by measuring ΔX. Z was estimated from the expected shape of the surface for the first calculation, given the known value of S. The slopes were then integrated in from the outer edges to determine the surface contour. Based on the new surface contour, Z was calculated anew and the procedure continued until the values converged.

Included in the data reduction code was a method of introducing random measurement uncertainties (around 0.5 mm); there was no significant effect on the deduced surface contour.

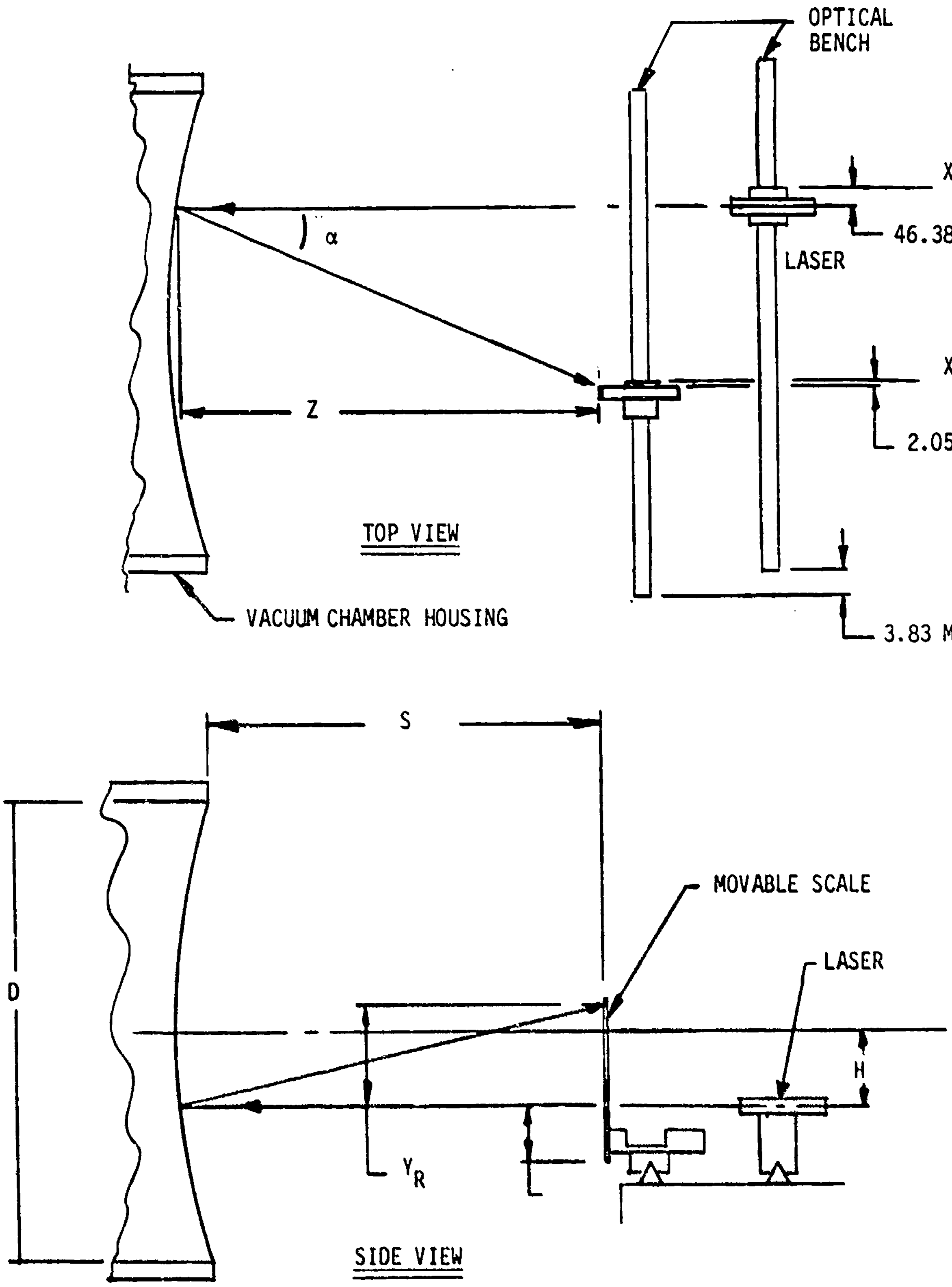


Figure 7. Slope-measurement optical setup.

The tests were accomplished in the following manner. The membrane was constructed and the outer edge of the gore defined (by analysis) and marked. The outer edges were taped in place along a circular mounting plate comprising the open end of the test chamber. In some cases, the membrane had to be stretched into position (for the paraboloids). A vacuum was then pulled in the chamber to a level so that the membrane was sucked into its desired depth. The depth in all cases except the heat-formed membrane was such to result in a F/D of about one (the chamber diameter, D, was 908.8 mm). A reference position on the optical bench was chosen so that when the laser was positioned there, the reflected spot appeared at a designated position on the laboratory wall, about 30 feet away. The chamber pressure was maintained with a needle valve so that the reference spot remained at that location throughout the test. (This is a much more sensitive measure of pressure than trying to monitor it using vacuum gages -- the design pressure for the paraboloid was about 477 Pa (0.005 atm or 0.069 psi).

A summary of the primary materials used in the tests is given in Table 1.

TABLE 1. SOURCES FOR FILMS AND TAPES USED

Material	Thickness	Surface	Trade Name	Source
Polyester Film	.006 mm (¼ mil)	VDA*	Mylar	G.T. Sheldahl
Polyester Film	.025 mm (1 mil)	VDA	Mylar	King-Seeley Thermos Co.
Polyester Film	.025 mm (1 mil)	Clear	Petra HS	Allied Fibers & Plastics
Polyester Film Tape	.025 mm (1 mil)	Heat Sensitive Adhesive	Mylar	G.T. Sheldahl
Polyester Film Tape	.006 mm (¼ mil)	Heat Sensitive Adhesive	Mylar	G.T. Sheldahl

*Vacuum-deposited aluminum

4.1 Paraboloids

The FLATE code showed that for a small number of gores, the paraboloid would require substantial stretching to mount it properly on the test chamber.

The smallest number of gores that could be used for the design being considered was 24 (36 were used on the 3-m diameter paraboloid for NASA). For less gores, the film could not be stretched into place by hand. Figure 9 shows the appearance of the inflated paraboloid.

Figure 9. 24 gore paraboloid.

Two paraboloids were tested. The first was constructed using the flat patterns for the "uniform material" model of the paraboloid (see Section 3.1). The second was constructed using the flat patterns with the "seam correction". In the first case, the rms deviation from a true paraboloid was measured to be 0.762 mm and in the second case 0.607. However, of more significance is the behavior of the deviation as shown in Figure 10.

The paraboloid constructed using the method of "uniform material" (the same as done for the NASA program) had the same W-shaped deviation curve as for the 3-m NASA paraboloid (see Figure 5). The rms-deviation is nearly identical to that found for the NASA 3-m diameter paraboloid (0.76 mm), implying that this deviation does not depend on scale. When the surface was measured for the second paraboloid, which had the "seam correction", the W-shaped curve flipped into a

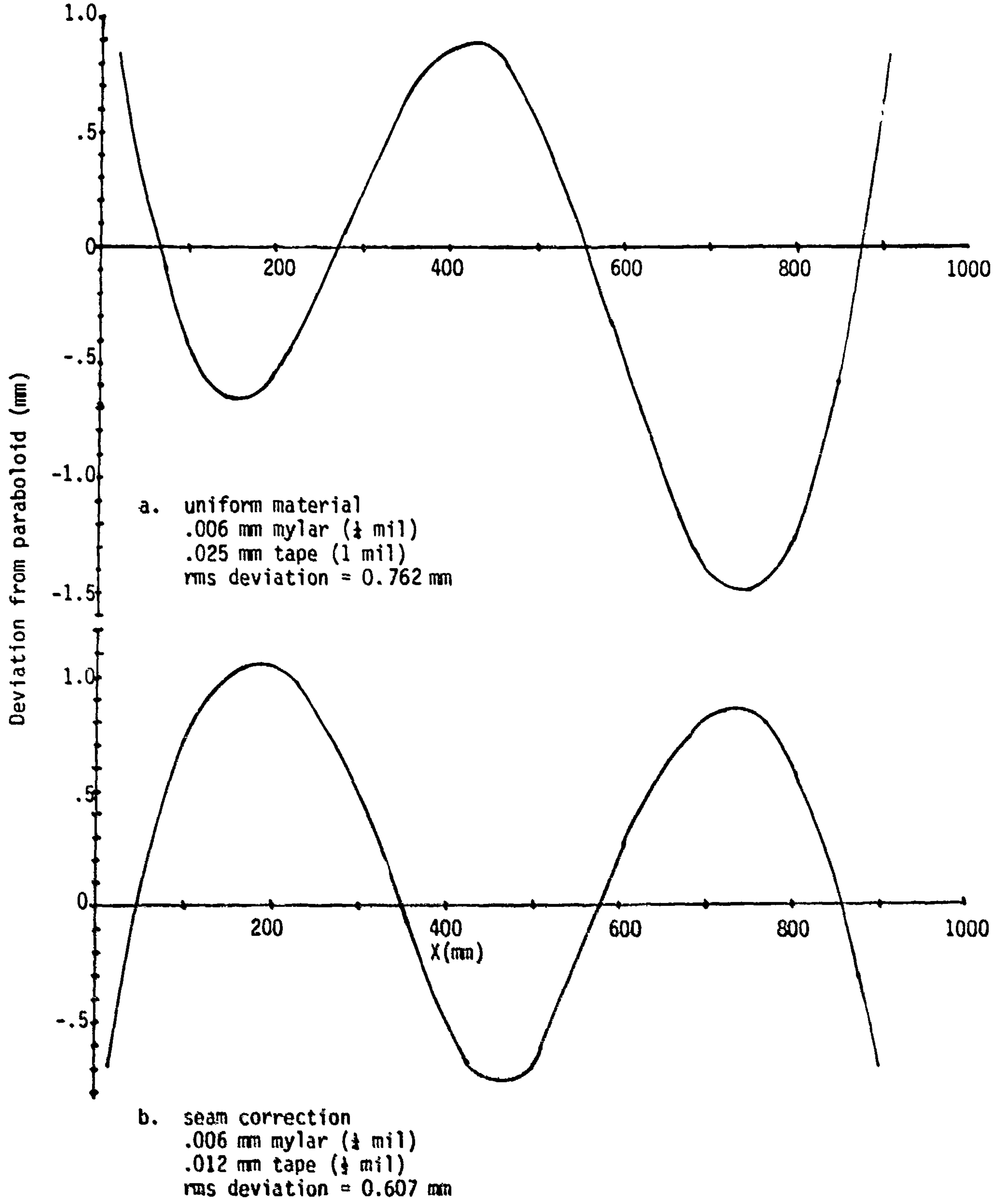


Figure 10. Comparison of paraboloids using two different flat patterns.

M shaped curve -- implying that the correction was too large. Clearly, the error is systematic; little scatter in the data is seen. In fact, it should be possible to linearly extrapolate between the two deviations to determine the gore pattern that will nearly eliminate the systematic errors shown. This remains to be done on the next phase. Tests below with the flat membranes show that when this is done, the residual surface error will be of the order of 0.1 mm.

4.2 Flat Membrane -- Welded Seam

In order to minimize the impact of the seams on the membrane, laser-welding of the gores was done to create a membrane with minimum seam material. Amorphous (unoriented) 0.025 mm (1-mil) mylar was cut into pie-shaped gores and sent to William E. Young & Co. for joining. The welded film was then mounted as usual on the test chamber and a vacuum pulled. However, the seams broke almost immediately (Figure 11). Apparently the welding procedure resulted in bonds too weak for this application, or the film material was thinned in places by the process.

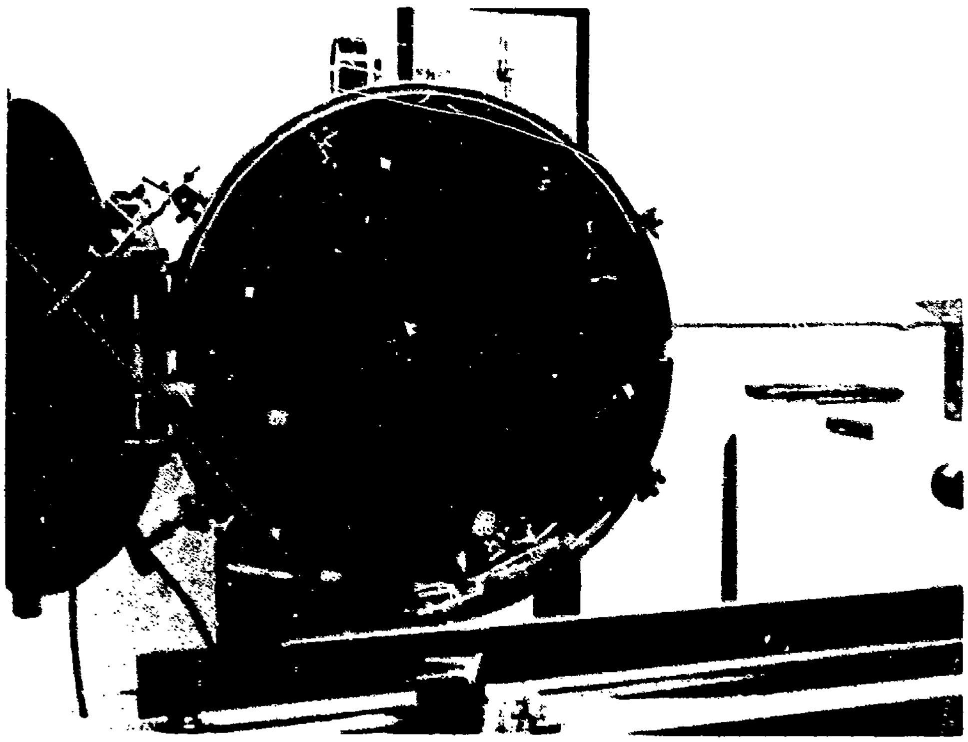


Figure 11. Welded flat membrane test

Measurements were made initially of a unseamed membrane of the same material (one piece). These data are not presented here since they were to be used as a reference for the membrane that exploded.

4.3 Flat Membrane - Nominal, Thin Film

Initially the membrane was constructed using the same material and procedures as for the paraboloids. A flat whole membrane of 0.006 mm (1/4 mil) mylar was mounted and its profile measured. Then, a similar membrane constructed out of 6 pie-shaped gores using 9.5 mm (3/8 in) wide tape of thickness 0.012 (1/2 mil). The reduced data was compared to the theoretical shape (equation 5) and the results shown in Figure 12. As seen, both membranes had a W-shaped deviation curve apparently resulting from a systematic deviation from the theoretical curve. Of more significance is the deviation between the two curves since this will determine the effect of seams, mounting technique, film properties variations, etc. upon accuracy. The rms deviation between the two curves is 0.233 mm.

4.4 Flat Membrane - Nominal, Thick Film

The test described in Section 4.3 was repeated using 0.025 mm mylar film and tape. The results are shown in Figure 13. Care was taken to cut out the gores in the same relative position on the film roll as for the whole disk. Care was also taken to mount both specimens so that "up" corresponded to the longitudinal direction of the roll of film. Again a W-shaped curve was obtained, but it was noticeably more skewed than for the other film. The deviation between the whole membrane and the one with gores was only about 0.13 mm rms. The skewness of the distribution could be caused by nonuniform mechanical properties in the plastic film, from one side of the roll to the other.

4.5 Flat Membrane - Prestretched Gores

To minimize the effect of the tape on the gore edges, this sample was constructed by first stretching the gores to their final pressurized length and then applying the tape. Thus, when the membrane is pressurized to its desired shape, the gores will be in tension but the tape will not. The film thickness was 0.006 mm (1/4 mil) and the tape thickness was 0.025 mm (1 mil). Again the resulting curve was W-shaped (see Figure 14), and the deviation between it and the reference was 0.268 mm rms.

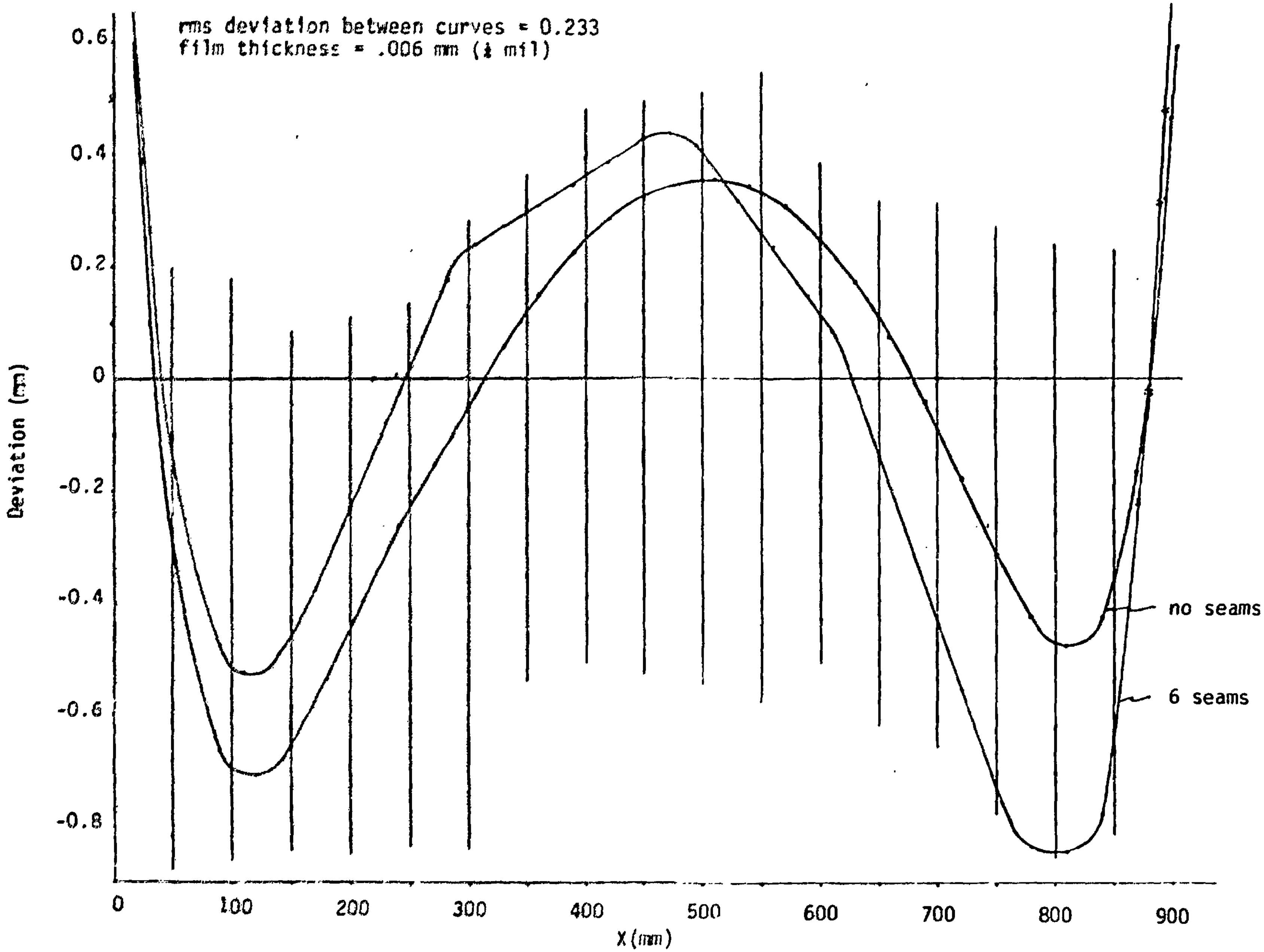


Figure 12. Performance of thin, flat membrane.

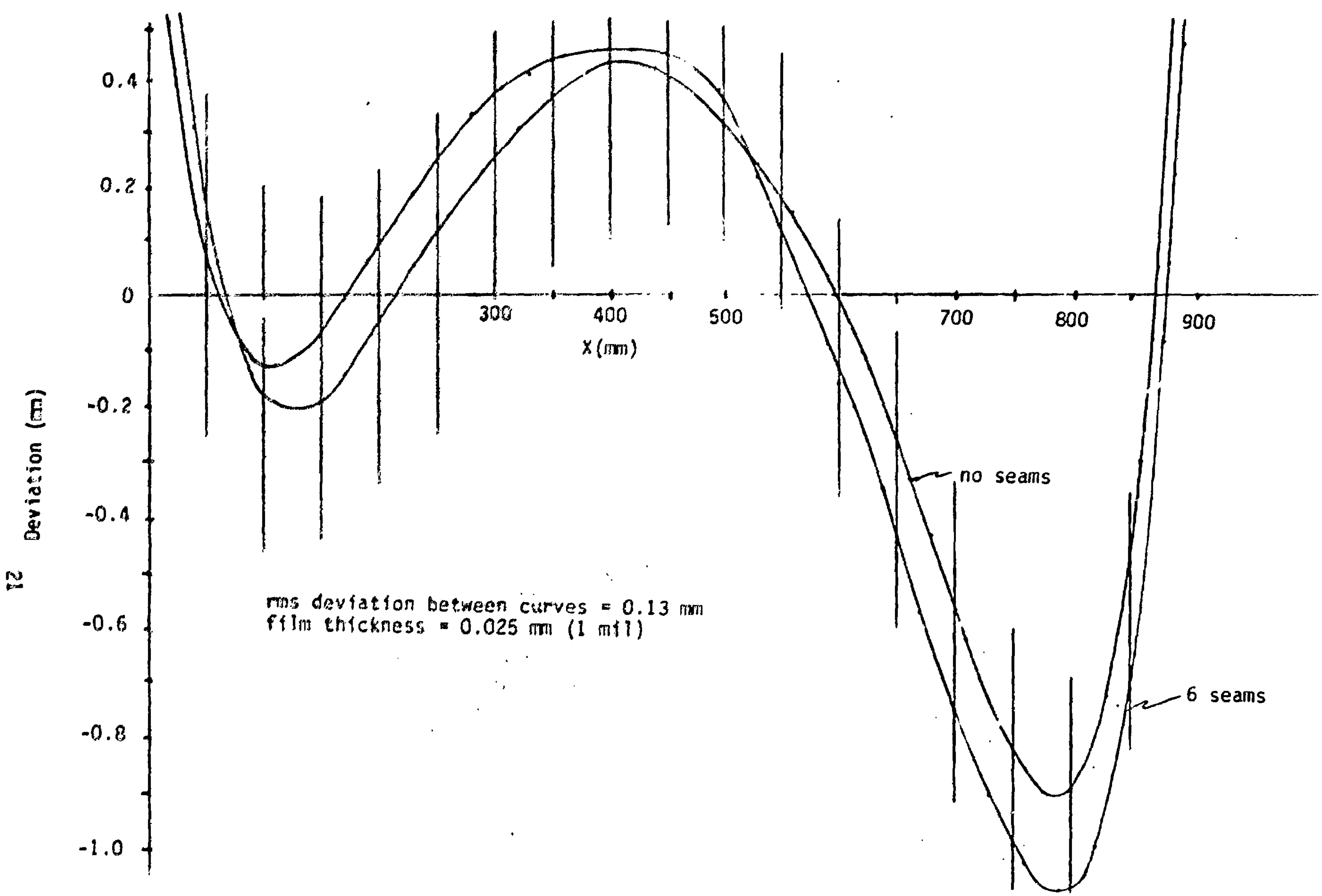


Figure 13. Performance of unformed, thick, flat membrane

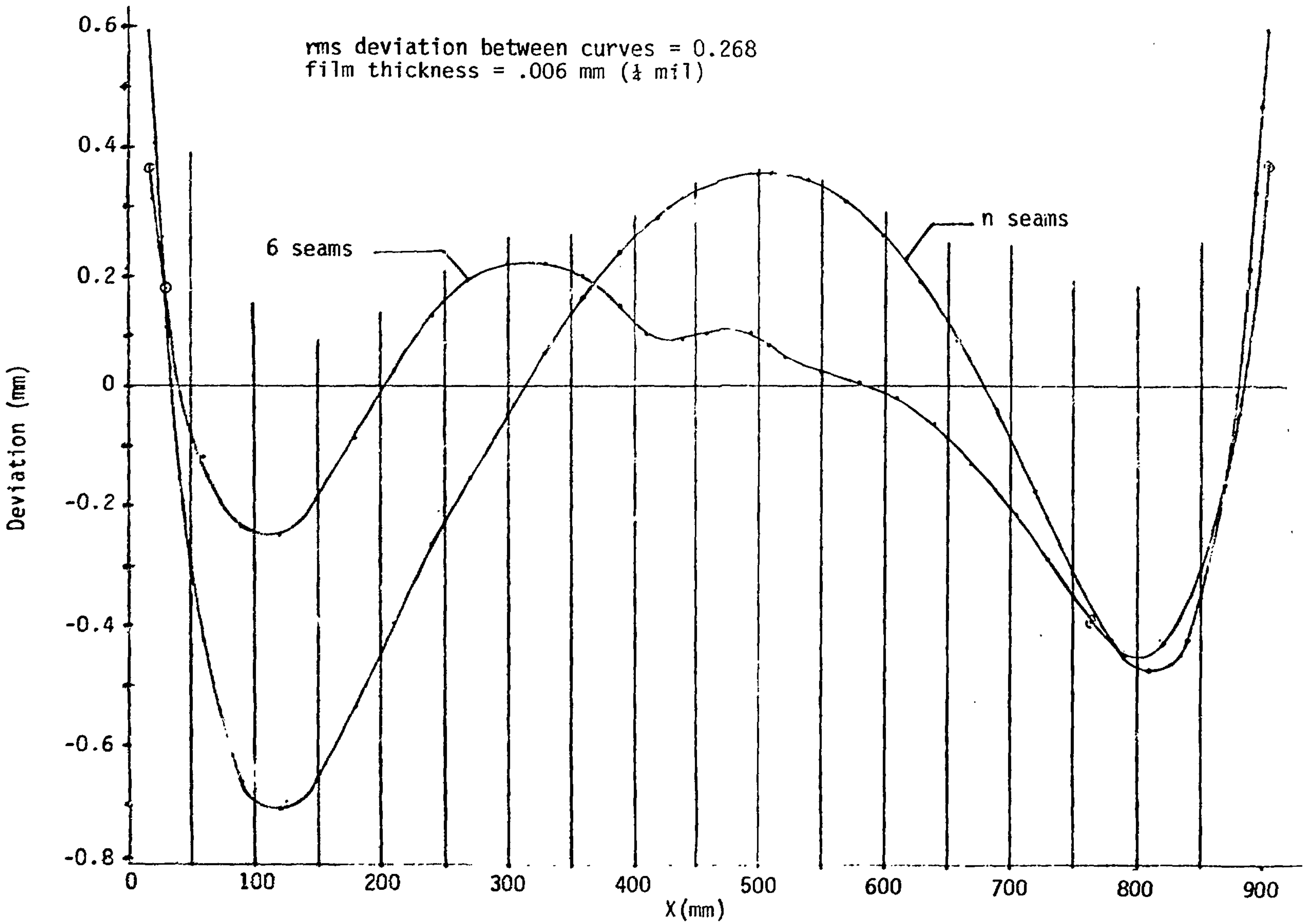


Figure 14. Performance of prestretched, thin, flat membrane.

4.6 Flat Membrane - Lattice-Reinforced Gores

In an attempt to equalize material properties in all directions, extra tape was added to the gores in a lattice fashion (see Figure 15). In this case

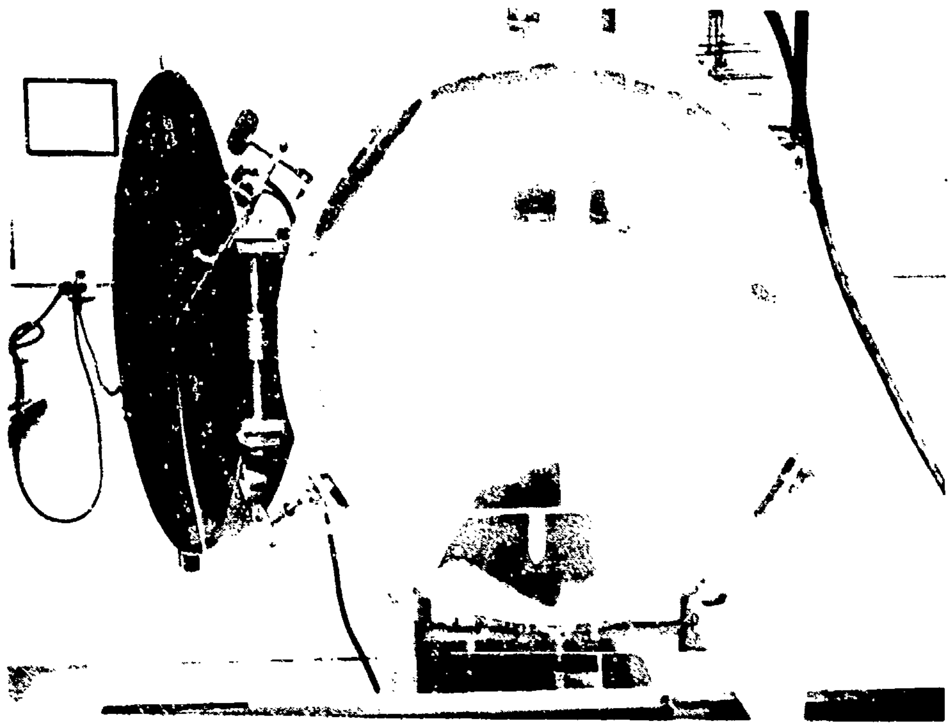


Figure 15. Lattice-inforced flat membrane.

the tape was 9.5 mm (3/8 in) wide and 0.012 mm (1/2 mil) thick. The results of the test are shown in Figure 16. Discontinuities associated with the tape are more pronounced, but the deviation from the reference curve has been somewhat reduced (to 0.208 mm rms).

4.7 Heat Formed Spherical Membrane

When heated, mylar will shrink as it tries to return to its disoriented state. In preparation for forming a spherical membrane, tests were run to determine the amount of shrinkage as a function of temperature and time. In general it was found that the percentage of shrinkage depended mainly upon temperature and reached its maximum value in a few minutes. Further heating at the same temperature

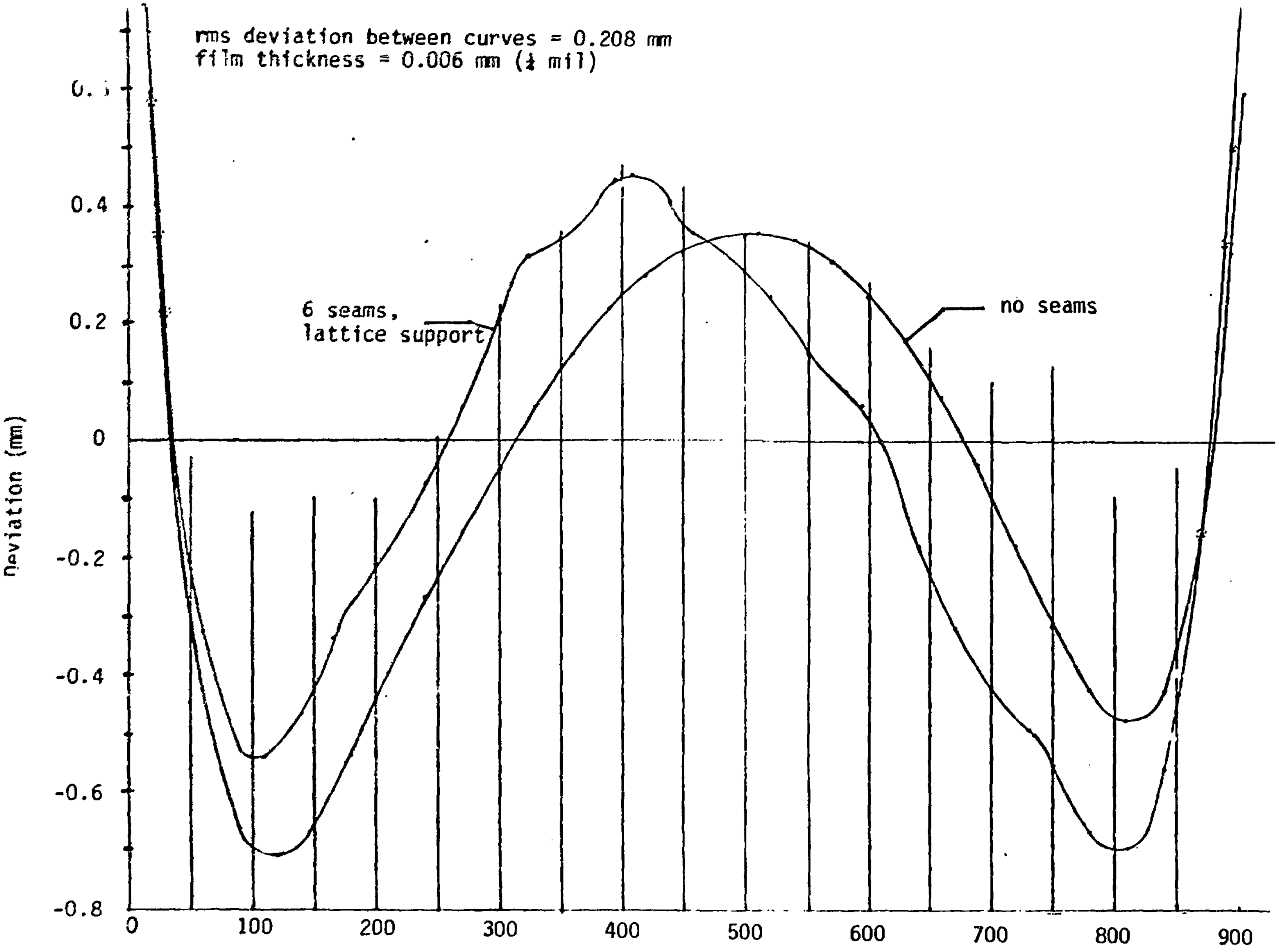


Figure 16. Performance of lattice-supported, thin, flat membrane.

did not result in further shrinkage. Figure 17 shows the results of the tests on

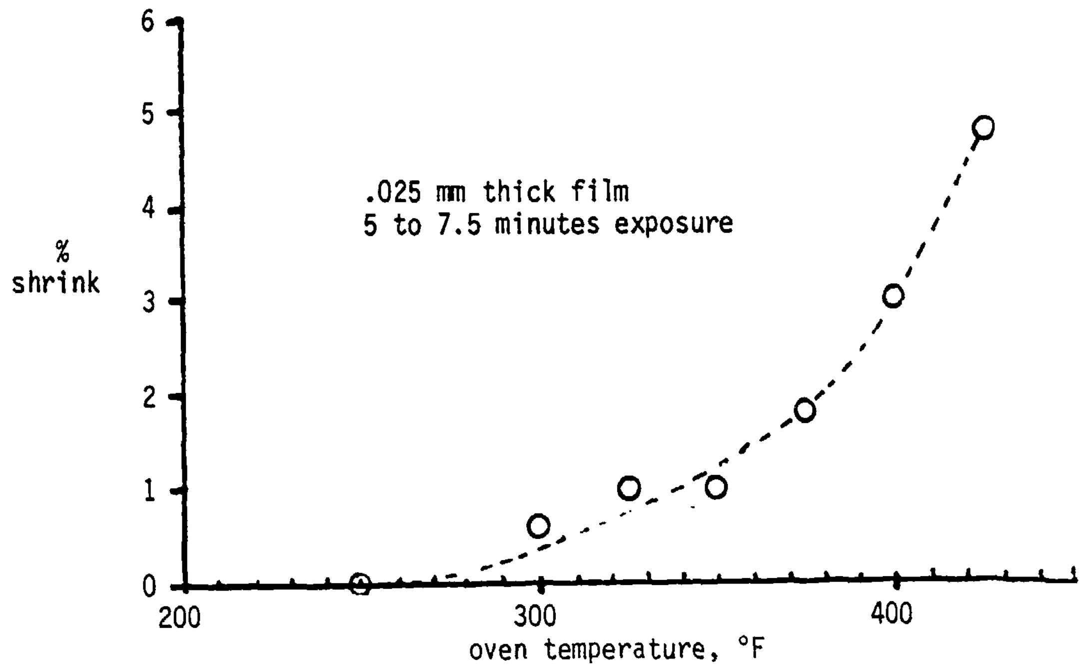


Figure 17. Mylar shrinkage from heating.

0.025 mm (1 mil) mylar that had been heated at the ambient temperature shown for a period of from 5 to 7.5 minutes. At temperatures above 425°F the material became crazed and lost its glossy shine. A temperature of 325°F was chosen for the forming and the resulting 1% shrinkage was sufficient to allow the film to match the surface against which it was forming.

The mold used was a 89.535 cm (35.25 in) diameter segment of a glass mirror with a radius of curvature of about 2.4 m (95 in). Both a continuous sheet of mylar and one of 6 gores were heat formed for five minutes at 325°F using this mold.

Figure 18 shows the deviations from the flat-membrane theoretical curve for the pressurized membranes. As might be expected, the deviations have switched from a W-shaped curve to a M-shaped curve. Probably at some higher inflation pressure, the theoretical curve could be matched nearly perfectly; however, this

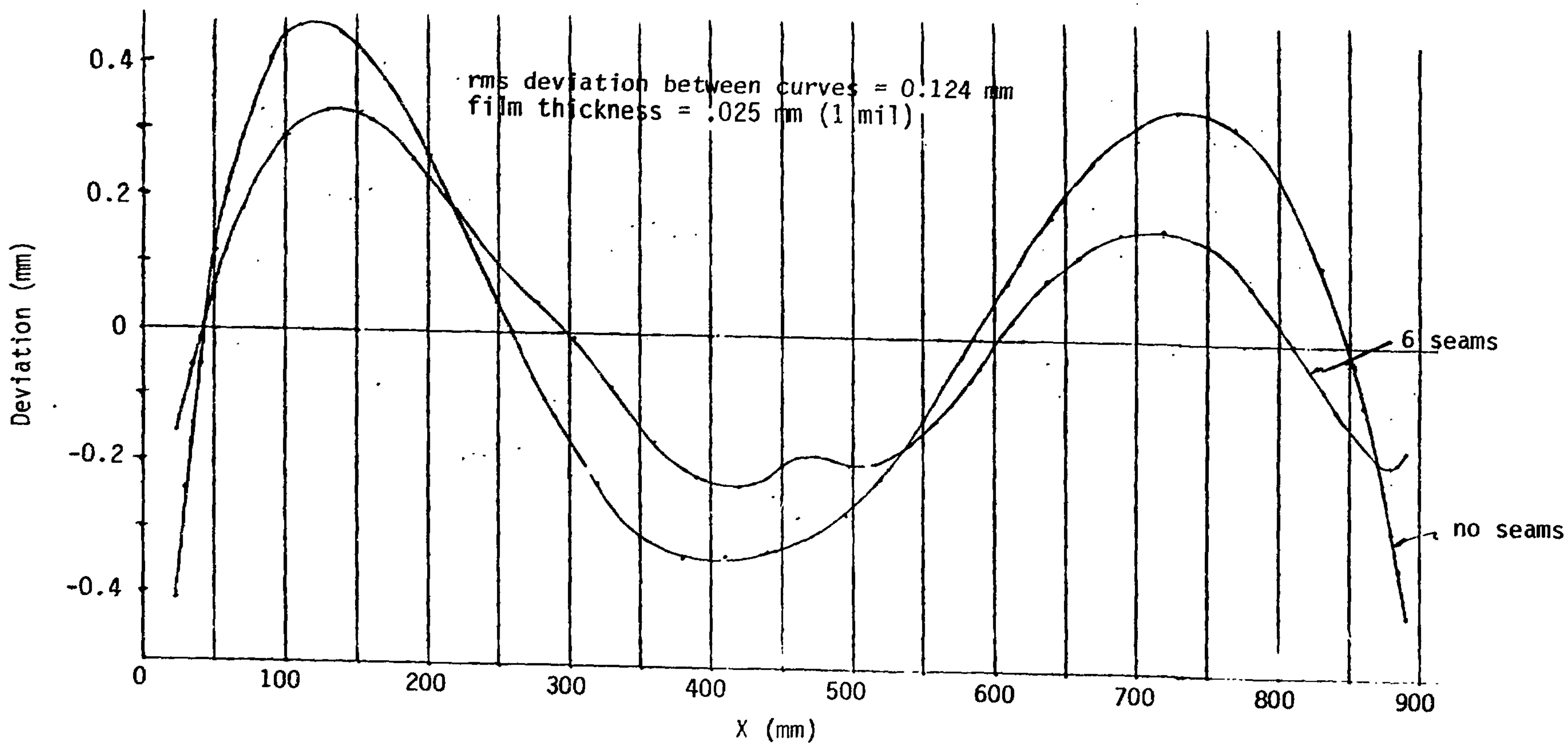


Figure 18. Performance of heat-formed, thick, flat membrane

is irrelevant to the current study. The resulting rms deviation between the seamed and the unseamed disks is 0.124 mm. It should also be noted that the material used was identical to that of Section 4.4, but the skewness of the deviations has disappeared, suggesting that an annealing of the plastic film under tension and heat to remove anisotropicities may be possible.

Figures 19 and 20 show the appearance of the thermal formed spherical surfaces. To the eye, these appeared the same as the unformed systems.

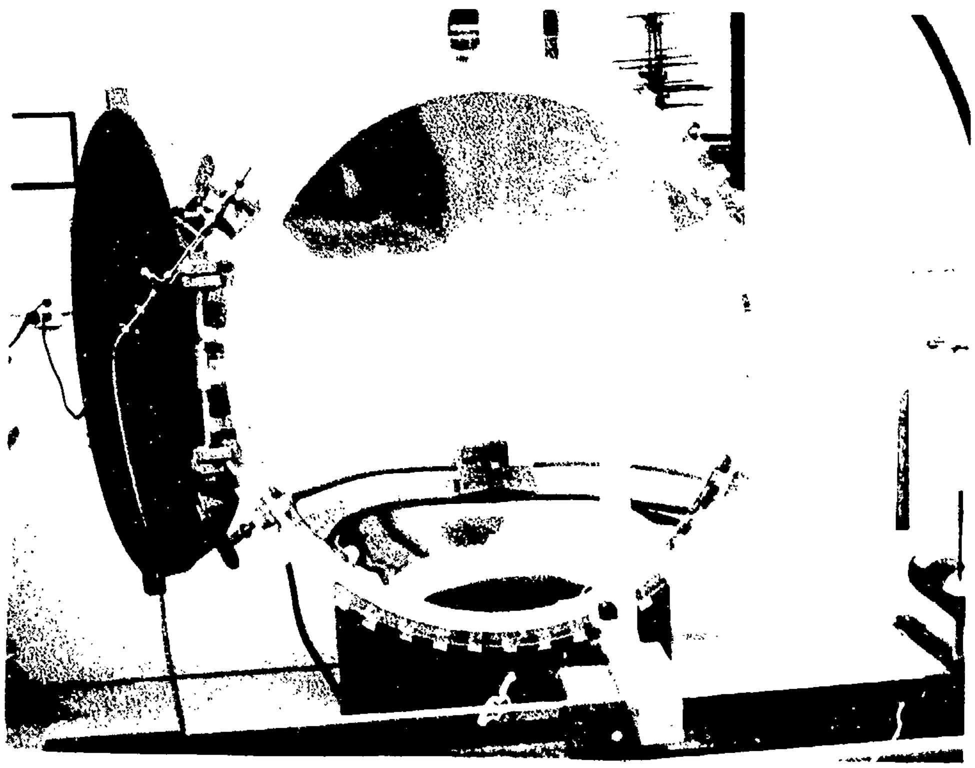


Figure 19. Thermal formed spherical; no gores.

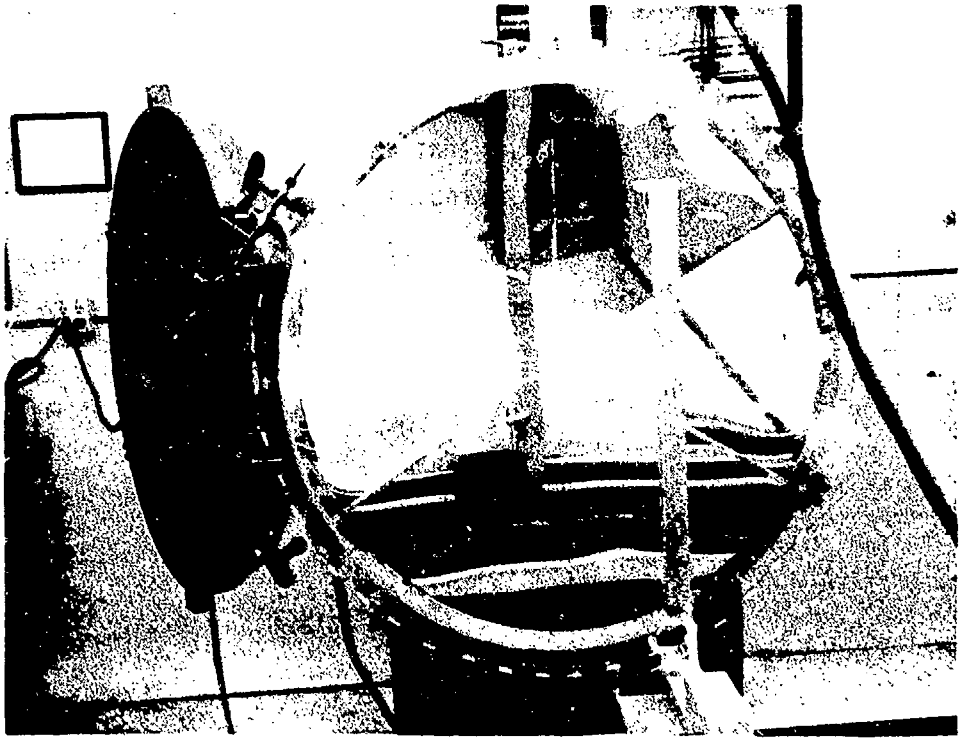


Figure 20. Thermal formed spherical; 6 gores.

5. CONCLUSIONS

The studies performed here show that methods are available to produce inflatable reflectors with surface inaccuracies of the order of 0.1 mm rms (cases with rms deviations of 0.124 and 0.130 mm were demonstrated). A better match to references was obtained using 0.025 mm film and 0.025 mm tape. The use of 0.006 mm film and 0.025 or 0.012 mm thick tape may have been more inaccurate because the discrepancy between film and tape thickness is greater and no corrections were made for tape properties in the comparisons. (This was done only for the paraboloids.) Or, it may be that the physical properties of the thinner film are more irregular than for the thick.

Heating of the film to form it showed an annealling effect which might be useful in removing modulus variations in the thin film. This could be done on flat specimens before gores are cut, or used to form gores to a desired shape to reduce the required inflation pressure.

Welded seams for the thin films do not appear feasible at present based upon the catastrophic failure of the welded membrane tested.

If the material nonuniformity is removed, the remaining errors appear to be mainly systematic and can be removed by appropriate choice of the flat pattern. Random errors associated with manufacturing tolerances do not appear to influence the accuracy of these reflectors at the 0.1 mm rms level.

6. RECOMMENDATIONS

The following work should be accomplished during Phase II.

6.1 Theoretical Analysis

Analysis deals primarily with two areas -- support of the testing and determination of the effect of temperature gradients.

6.1.1 Analysis in support of testing. Improved methods are needed to calculate the flat patterns needed to provide the desired shape. The primary shapes of interest are the inflated paraboloid and the noninflated flat membrane. The models must include the effect of nonuniform properties, both due to the virgin material and due to the addition of seams. Some improvement is needed to the data reduction codes in order to display the data in the proper format.

6.1.2 Thermal/structural analysis. A thermal expansion term will be included in the FLATE code. The effect of realistic thermal gradients upon the resulting inflated shape of the reflector will then be calculated. Although the inflatable structures should be less affected by thermal expansion than rigid structures, this has not yet been demonstrated.

6.2 System Analysis

Given several typical missions for these reflectors as defined by the USAF, system candidate designs should be made. Studies should define not only the system overall configuration but the effect of the interfaces between the inflatable and hard structures. Effects of vehicle dynamics should be quantified. The size, weight, and conceptual design of system components should be estimated.

6.3 One-Meter Membrane Testing

Additional testing should be performed using the Phase I facility setup to separate the effects of material nonuniformities, manufacturing errors, film thickness/tape thickness, and thermal annealing or forming upon membrane accuracy. Such tests would include multiple measurements on the same configuration, a more substantial analysis of the optical setup and its contribution to error, preparation of samples from annealed sheets, measurements of material moduli in various

directions from various positions across a roll of film (both before and after annealing), and additional paraboloid tests using improved flat patterns.

6.4 Three-Meter Membrane Testing

This work will be on paraboloids only and will extend the best methods determined during the one-meter testing to the larger 3-meter testbed. More extensive mapping of the surface will be done to determine the accuracy at other altitudes and overall.

6.5 Torus Development

The outer diameter of an inflated reflector needs to be maintained by a hard structure. A promising candidate for this is the inflated and then rigidized laminated torus. Work was started to develop this on the USAF ITV program and its feasibility was established during the recent NASA contract on inflatable membranes. However, such systems must be built on a laboratory scale and studied to obtain data for their design and use with inflatable reflectors.

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3. Robert Kyman and James E. Houmard, "Inflatable Foam-Rigidized Approach to Solar Concentrators", Progress in Astronautics and Aeronautics, Vol. 11, Power Systems for Space Flight, edited by M. A. Zipkin and R. N. Edwards, 1963.

4. Raymond J. Roark, Formulas for Stress and Strain, McGraw-Hill Book Co., N.Y., 1971.

APPENDIX A

PLASTIC FILM PROCESSORS CONTACTED IN SURVEY

Company	Contact/Phone
Allied Chemical Los Angeles, CA	(213)685-8510
Aetna Plastics Corp. Cleveland, OH	(Distributors only) (216)781-4421
American Hoechst Corp. Newark, DE	(302)834-5900
Blank, Arthur & Co. Boston, MA	(Film products only) (617)254-4000
Cadillac Plastic & Chemical Birmingham, MI	(Distributor only) (313)646-5100
Dick Simon Assocs. Caldwell, NJ	(201)228-2440
Dayton Plastics, Inc. Dayton, OH	(Distributor only) (513)276-3921
DuPont Wilmington, DE	Clayton Roth (803)667-7254 Bob Schilpp (Product Mgr.) (302)774-7464
ICI Americas, Inc. Wilmington, DE	Tom Rittman (302)575-3000
Inter-American Marketing Systems, Inc. New York City, NY	(212)482-8404
Kaufman Glass Co. Wilmington, DE	(Film products only) (302)654-9937
Lustro Plastics Co. Valencia, CA	(4 mil minimum) (213)365-1106
Midland Plastics, Inc. Brookfield, WI	(Distributor only) (414)781-6520
NTS Plastics Products Bronx, NY	(Distributor only) (212)892-3838
Plastics Manufacturers, Inc. Philadelphia, PA	Bill Seiler (215)438-1082
Plastic Suppliers Blackwood, NJ	(Distributor only) (609)931-0498

Rhone Poulanc, Inc. Monmouth Jct., NJ	Eric Bartholomay (201)297-0100
N. Teitebaum & Sons, Inc. Bronx, NY	(212)992-6800
3M Co. St. Paul, MN	(612)733-1110
Ain Plastics, Inc. Mount Vernon, NY	(Distributor only) (800)431-2451
Allied Plastics Supply Bronx, NY	(Do not make film) (212)991-5100
Allied Corp. Morristown, NJ	Frank Gondirahin Dave McKee (201)455-2298 West Coast Office, Ed Healey (213)891-7636
American Acrylic Corp. West Babylon, NY	(Sheets only) (516)422-2200
Auburn Plastic Engineering Chicago, IL	(Distributor only) (312)254-4900
Commercial Plastics & Supply Corp. Cornwells Heights, PA	(215)638-0800 (California office) (213)532-9151
Crystal-X Corp. Darby, PA	(Polyethylene only) (215)586-3200
Dimensional Plastics Corp. Hialeah, FL	(Panels) (305)691-5961
Engineered Plastics, Inc. Gibsonville, NC	(Do not make film) (919)449-4121
Franklin Fibre Corp. Wilmington, DE	(Distributor only) (302)652-3621
Hastings Plastics Co. Santa Monica, CA	(Distributor only) (213)829-3449
Kryptonics, Inc. Boulder, CO	Chuck Demerist (303)442-9173
Polytech, Inc. Owensville, MO	(Sheets only) (314)437-2159
SGL Homalite Div. Wilmington, DE	(Sheets only) (302)652-3686

U.S. Plastic & Chemical Corp. Putnam, CT	(203)928-2707
Almac Plastics, Inc. Long Island City, NY	(Distributor only) (212)937-1300
Acrilex, Inc. Jersey City, NJ	(Distributor only) (201)333-1500
Island Extrusion Corp. Island Park, NY	(Do not make film) (212)895-5957 (516)431-9183
Meyercord Co. Carol Stream, IL	(312)682-6200
Technical Plastic Extruders, Inc. Newark, NJ	(5 mil minimum) (201)589-5800
William E. Young & Co. New Jersey	William Young (201)922-1234